C = 470pF and using
kHz, ω_0 = 1 and aR =

aR
Ideal: 15.05kΩ E96 std. value: 15.0kΩ
Ideal: 12.19kΩ E96 std. value: 12.1kΩ
Ideal: 17.42kΩ E96 std. value: 17.4kΩ
Ideal: 10.53kΩ E96 std. value: 10.53kΩ

a = 1/Q => aR = R/Q.

)22 dual and TLE2024
ons tion. Although
orst case total power
less compared to a
mented around three
suming in worst case
active elements would

for only 250µA supply
pecially at low supply
The only consideration
µs. However, this is
2.5V supplies.

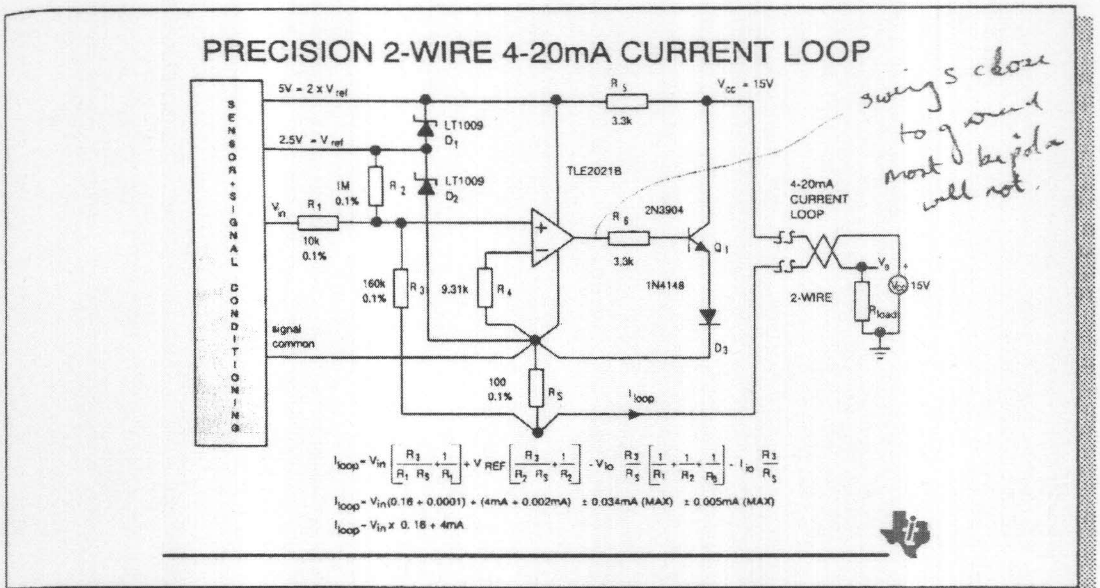

Figure 38 - Precision 2-Wire 4 to 20 mA Current Loop

LT1009C2 2.29
MC 7.03

(9.23)

What is a Current Loop?

Often information from an analog sensor must be sent over a distance to the receiving circuitry. For many applications, the most feasible method involves converting voltage information to a current before transmission. The most commonly used current loop interface standard consists of a minimum of two wires providing both the power supply for the sensor and signal conditioning circuit as well as transferring the information sensed in form of a current, which varies proportionally with the measured signal. The current in the loop varies usually from 4mA, corresponding to no signal, to 20mA for full scale - referring to the well known 4 to 20mA current loop. Up to 4mA of the loop current can be used for supplying the sensor, signal conditioning and voltage-to-current converter.

Notes

Precision 4 to 20mA Current Loop

The circuit presented provides a 4 to 20mA output current for a 0 to 100mV input voltage. By modifying R_1, R_2 and R_3 the input range or the output current can be adjusted. The total error is kept very low provided that the recommended precision components are used.

The employed Excalibur op amp, the TLE2021B, is a high performance op amp well suited for this type of application. The TLE2021B is here configured as a voltage-to-current converter, transmitting a very stable loop current, I_{loop}, proportional with the input voltage, V_{in}. The converter's transconductance or "gain" can be adjusted by R_1 and its current-offset varies with R_2. Resistor R_4 reduces the influence of the op amp's input bias current to that of its input offset current.

The loop current is divided up in three major paths: The primary current path is through transistor Q_1, whilst the secondary paths are via the reference and through the op amp. All current flowing through R_S is within the controlled and regulated 4 to 20mA current loop. The current flowing through R_3 is outside the loop control and contributes to the circuit's total error. This current can be taken into consideration in the design equations but with the chosen component values, its error becomes insignificant.

High system accuracy and stability is achieved without trimming by using two LT1009 voltage references in series producing a precision +5V reference. This implementation not only provides a stable 0.2% precision reference for the voltage-to-current converter but also ensures that picked up noise and hum from long loop wires are suppressed from the op amp supply by the reference element's low dynamic impedance. In addition, the reference and its +2.5V centre point are available for external signal conditioning circuitry, provided that a limited current is taken. The converter itself needs a minimum of 630µA (400µA for the reference and 230µA for the op amp), leaving (4 - 0.63)mA = 3.37mA to be used by additional circuitry. If really low power is required, the LT1009 voltage references should be replaced by LT1004s reducing the quiescent current consumption to basically that of the TLE2021B op amp or 240µA.

Why use the Excalibur TLE2021Op Amp?

- **Common Mode Input Voltage to Negative Supply Rail**
  By analysing the application it is seen that the input common mode voltage is zero volt.

- **+5V Single Supply Capability**
  This op amp feature eliminates the need for a third negative supply wire or a charge-pump creating a negative rail from the positive. Also, the low minimum operational voltage is utilized.

- **Output Swing Close to the Negative Rail**
  By analysing the circuitry it is seen that an output swing down to two V_{be} from the negative rail is required. Few dual supply op amps can actually swing that low.

- **Low Power Consumption**
  A total of 4mA is available for the converter and sensor interface. TLE2021 uses less than 230µA leaving more current for other parts of the circuit.

- **Low and Stable Input Offset Voltage**
  From the output current expression on the figure, it is clear that low input offset voltage is required. A 1mV offset voltage would contribute with a current error of 0.17mA. The TLE2021B with its maximum input offset voltage of 100µV (200µV max @ 5V supply) gives low error. Additionally, its offset voltage also remains stable with temperature and time featuring 2µV/°C and 5nV/month typical drift.

Design Details

Assuming that the voltage at the non-inverting input terminal of the TLE2021B is of zero volt relative to "Signal Common", and that $I_{R_S} = I_{loop}$, the sum of the currents at the non-inverting terminal gives:

$$\frac{V_{in}}{R_1} + \frac{V_{ref}}{R_2} - \frac{I_{loop} R_S}{R_3} = 0 ;$$

Solving this with respect to I_{loop} gives:

$$\boxed{I_{loop} = V_{in} \frac{R_3}{R_1 R_S} + V_{ref} \frac{R_3}{R_2 R_S}} \qquad (1)$$

The design equations specifying the resistor values can be derived from (1). Assuming V_{ref} = 2.5V and V_{in} ranges from 0- to 100mV, it follows:

(a) $$I_{loop}(min) = V_{ref} \frac{R_3}{R_2 R_S} \quad \Rightarrow \quad 4mA = 2.5 \frac{R_3}{R_2 R_S} ;$$

(b) $$I_{loop}(max) = V_{in}(max) \frac{R_3}{R_1 R_S} + 4mA \quad \Rightarrow \quad 20mA = 0.1 \frac{R_3}{R_1 R_S} + 4mA ;$$

Notes ________________________________

Equation (a) and (b) have in in total four unknown resistor values. By chosing two of them the equations decide on the other two. The basic guidelines applied for the choice of the resistor set satisfying (a) and (b) are:

R_S should be small to minimise its voltage drop. Two problems are associated with a high voltage drop across R_S. Firstly, it causes variation in the reference diodes current with the loop current and hence affects their stability. Secondly, a high voltage drop increases the current flowing outside the control loop through R_3. However, very small resistor values are not available with high accuracy - say 0.1%, but a good compromise is 100Ω.

R_1's value is a compromise between minimising errors resulting from the op amp's input offset currents, I_{io}, to a level below that of the op amp's offset voltage, and simultaneously not loading the source. With I_{io}(max) = 3nA, a 10kΩ resistor gives only 30µV offset error compared with the op amp's 200µV (max) offset voltage at 5V supply. $R_4 = R_1||R_2||R_3$ ensures that only input offset current rather than input bias current contributes to the error.

R_2 should maximum be 1MΩ to allow a 0.1% high precision resistor to be used.

R_3 should be as high as possible to limit the current flowing outside the control loop but satisfy the same criteria as for R_2.

A set of values satisfying the above criteria and equation (a) and (b) is:

$$R_S = 100\Omega; \quad R_1 = 10k\Omega; \quad R_2 = 1M\Omega; \quad R_3 = 160k\Omega; \quad R_4 = 9.32k\Omega;$$

R_5 delivers the current required for the LT1009 shunt references, the op amp plus additional current for the sensor and its interface circuit. This current is stable with constant V_{in} but as the voltage drop across R_S varies with I_{loop}, the drop across R_5 varies as well. This in turn causes the current through the LT1009 references to shift accordingly. To avoid changes in the reference voltage this current must be kept fairly stable; hence the drop change across R_5 must be minimised placing constraints on a minimum power supply voltage and the value of R_{load}. Choosing R_5 = 3.3kΩ causes the current in the LT1009 references to vary by only 700µA, provided that R_{load} = 50Ω. This choice also allows for up to 1.5mA reference current to be used for the sensor and its interface.

Error budget

The op amp's offset error, V_{io}, modifies the loop current, I_{loop}, of equation (1) as the voltage at the non-inverting input is $\pm V_{io}$ rather than zero volt with respect to Signal Common assumed for (1). If the op amp's input offset current, I_{io}, is taken into consideration, it should be summed with the other currents at the non-inverting terminal of the op amp. This yields:

$$\frac{V_{in} - V_{io}}{R_1} + \frac{V_{ref} - V_{io}}{R_2} - \frac{I_{loop} R_S + V_{io}}{R_3} - I_{io} = 0 ; \qquad =>$$

$$I_{loop} = V_{in}\frac{R_3}{R_1 R_S} + V_{ref}\frac{R_3}{R_2 R_S} - V_{io}\frac{R_3}{R_S}\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}\right) - I_{io}\frac{R_3}{R_S}\ ; \qquad (2)$$

An additional error source adding to I_{loop} of (2) is the current bypassing the control loop through R_3. All current passing through R_S is inside the control loop. In equation (1) we assumed that $I_{loop} = I_{R_S}$ but a more correct expression is:

$$I_{loop} = I_{R_S} + I_{R3} \quad \text{or} \quad I_{loop(3)} = I_{loop(1)} + I_{R3}\ ;$$

where $I_{loop(1)}$ is I_{loop} given by (1). By ignoring the insignificant effect from the op amp's offset error on the bypass current error: $V_{R3} = V_{R_S} = I_{loop(1)} R_S$ resulting in:

$$I_{loop(3)} = I_{loop(1)} + I_{loop(1)}\frac{R_S}{R_3} \quad <=> \quad I_{loop(3)} = I_{loop(1)}\left(1 + \frac{R_S}{R_3}\right)\ ;$$

Substituting $I_{loop(1)}$ with I_{loop} of (1) yields:

$$I_{loop(3)} = V_{in}\left(\frac{R_3}{R_1 R_S} + \frac{1}{R_1}\right) + V_{ref}\left(\frac{R_3}{R_2 R_S} + \frac{1}{R_2}\right)\ ;$$

By adding the errors contributed by V_{io} and I_{io} in equation (2), ignoring the insignificant effect from the bypassed loop current on these errors, we have:

$$\boxed{I_{loop(3)} = V_{in}\left(\frac{R_3}{R_1 R_S} + \frac{1}{R_1}\right) + V_{ref}\left(\frac{R_3}{R_2 R_S} + \frac{1}{R_2}\right) - V_{io}\frac{R_3}{R_S}\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}\right) - I_{io}\frac{R_3}{R_S}}$$

Notes

I_{R3}	$(R_S/R_3)\ I_{loop}$	2.5	12.5	µA
Total Worst Case Error in I_{loop}		±61.6	±119.7	µA
Total Worst Case Error in % of Ideal I_{loop}		±1.5	±0.6	%

Note: Low Level = 4mA, Full Scale = 20mA.

The worst case untrimmed error of ±0.6% for full scale at 25°C is mainly dominated by resistor tolerances and the op amps input offset voltage. The chance of the individual errors being worst case and contributing in the same direction or adding up with the same sign is unlikely - so typically, the performance will be much better. However, by trimming R_2 for low levels (4mA) and R_1 for full scale (20mA) all of the above errors can be eliminated, reducing inaccuracy to drift with time and temperature of the same parameters. Such a trimmed circuit can achieve a similar accuracy as the untrimmed one at 25°C but over a 0°C to 70°C temperature range.